Dynamic Pressure Metrology

V. E. Bean

Abstract. According to the ANSI MC88.1-1972 standard *A Guide for the Dynamic Calibration of Pressure Transducers*, the properties to be determined when calibrating a dynamic pressure transducer are sensitivity, amplitude as a function of frequency, phase as a function of frequency, resonant frequency, damping ratio, rise time and overshoot. A static calibration yields only the sensitivity. The properties of dynamic pressure transducers and various methods for determining them are reviewed.

1. Introduction

The principal activity in a static pressure calibration laboratory at a national metrology laboratory involves piston gauges (pressure balances, dead weight testers) with uncertainties expressed in parts per million. The principal activity in a dynamic pressure calibration laboratory involves pressure transducers with uncertainties expressed in per cent.

The amplitude and frequency of dynamic pressure calibration requirements are widely varied, for example, from 13 Pa at 50 kHz for aerospace applications to 1 GPa at 100 MHz for studies on explosives. Figure 1 is an outline in pressure and rise-time space of the dynamic pressure calibration requirements reported by the participants at a workshop on dynamic pressure measurement held at the National Institute of Standards and Technology (NIST) [1].

A pressure transducer is a mechanical structure. When used to measure dynamic pressure, it will "...deflect, vibrate, resonate, conduct sound, experience stress and strain, and transfer force and motion. Sensor structures act differently at low, medium, and high frequencies, manifesting static, structural, and acoustic modes of behavior" [2].

Clearly, we must understand the properties of a transducer before we can calibrate it. In this paper, we review the properties of pressure transducers and methods to determine them.

V. E. Bean: National Institute of Standards and Technology, Gaithersburg, MD 20899, USA.
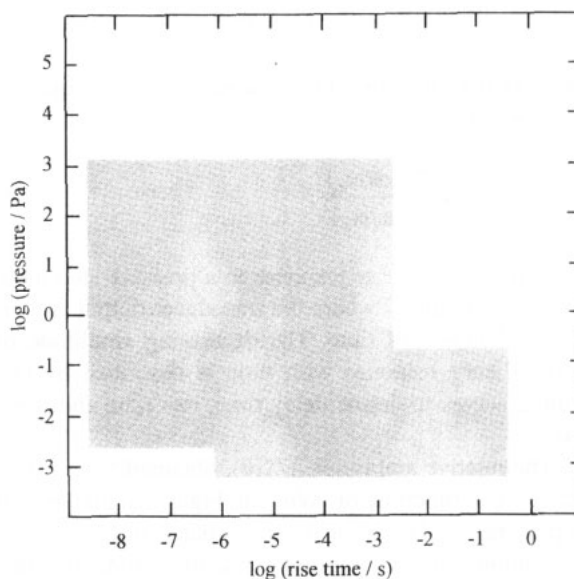
Figure 1. The outline in pressure and rise-time space of the dynamic pressure calibration requirements reported by the participants at the NIST workshop on dynamic pressure measurement.

2. Dynamic Pressure Transducers

The typical pressure transducer can be represented by a mechanical model consisting of an inertial mass, a spring, and a viscous resistance [3-6]. The mass can be displaced by a step input, corresponding to a transducer

being subjected to a shock wave, or by an oscillatory driving force, corresponding to a transducer being installed in an internal combustion engine. The shock wave case is known as *free vibration*; the oscillatory case is known as *forced vibration*.

The motion of the mass can be described by a differential equation whose solution is the transducer output. For the free vibration case it is

$$x = X \exp\left(-\zeta\omega_n t\right)\sin\left[\left(1-\zeta^2\right)^{1/2}\omega_n t - \phi\right], \tag{1}$$

where x is the instantaneous amplitude of the output, X is the maximum amplitude of the output, ζ is the damping ratio, ω_n is the undamped natural frequency, t is the time and ϕ is the phase angle by which the output lags the input.

For the forced vibration case, the solution of the differential equation is

$$x = X \sin\left(\omega t - \phi\right), \tag{2}$$

where X is the amplitude of the steady oscillation and ω is the frequency. The term X can be expressed as

$$X = \frac{X(0)}{\sqrt{\left[1-\left(\omega/\omega_n\right)^2\right]^2 + \left[2\zeta\omega/\omega_n\right]^2}}, \tag{3}$$

where $X(0)$ is the transducer output at zero frequency. The phase lag is

$$\phi = \arctan\frac{2\zeta\left(\omega/\omega_n\right)}{1-\left(\omega/\omega_n\right)^2}. \tag{4}$$

Typical transducer response to a pressure step input is shown in Figure 2 where the transducer output is plotted as a function of time. The decreasing amplitude of the oscillatory response with time is described by (1). Figure 2 serves to define delay time, rise time and overshoot.

The relative amplitude $X/X(0)$, obtained from (3), is plotted as a function of ω/ω_0 in Figure 3 for several damping ratios. The resonant frequencies are defined by the locations of the amplitude maxima along the frequency axis. Both the resonant frequencies and the amplitudes are functions of the damping ratio.

Figure 4 is a plot of (4) as a function of ω/ω_0 for several damping ratios.

The transducer properties to be determined in the calibration of a dynamic pressure transducer may well depend upon the particular application. As a general guide, the ANSI MC88.1-1972 standard suggests that the following parameters need to be determined [3]:

(a) Sensitivity: the ratio of the change in the transducer output to a change in pressure.
(b) Amplitude as a function of frequency, as shown in Figure 3.
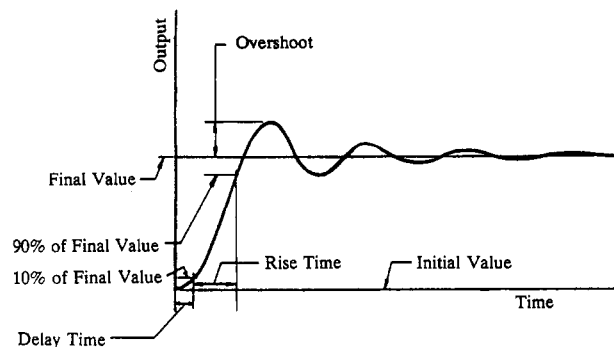(c) Phase as a function of frequency, as shown in Figure 4.

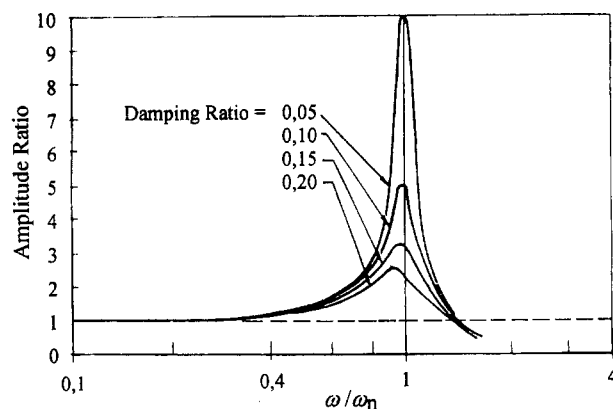**Figure 2.** Pressure transducer response to a shock wave plotted as a function of time.

Figure 3. Relative amplitude $X/X(0)$, plotted as a function of ω/ω_0 for several damping ratios.
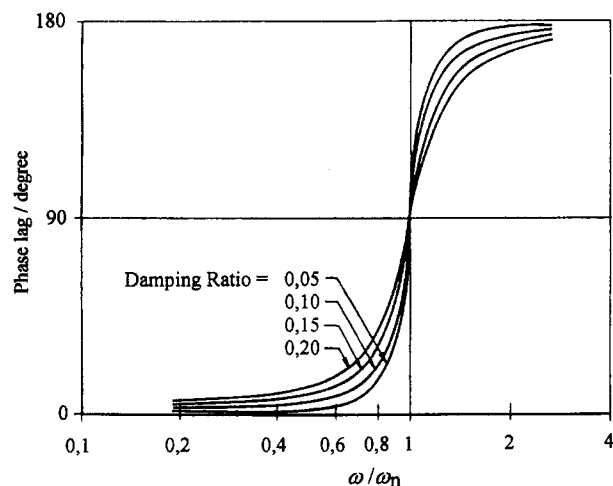

Figure 4. Phase lag ϕ, plotted as a function of ω/ω_0 for several damping ratios.

(d) Resonant frequency, obtained from the ringing frequency seen in Figure 2 or from the location of the maximum in Figure 3.

(e) Damping ratio, obtained from the logarithmic decrement of the curve in Figure 2.

(f) Rise time, defined in Figure 2.

(g) Overshoot, defined in Figure 2.

A static pressure calibration yields only the sensitivity. A dynamic pressure generator, with its associated measurements, is required to determine the other six parameters.

3. Dynamic Pressure Generators

Dynamic pressure generators are divided into two classes: aperiodic and periodic.

3.1 Aperiodic pressure generators

Aperiodic generators create pressure steps or single pressure pulses resembling a half-sine wave and include the shock tube, quick-opening valve devices, explosive devices and the drop hammer.

Shock tube. The shock tube, in its simplest form, consists of a straight tube of uniform cross-section containing a diaphragm which divides the tube into two compartments [7-9]. Initially, the gas pressure in one compartment is higher than in the other. When the diaphragm is ruptured, the expansion of the high-pressure gas into the low-pressure compartment creates a shock wave that travels faster than the expanding gas. The shock wave is reflected by the closed end of the tube resulting in an increased pressure behind the reflected shock wave.

The length of time the pressure remains constant behind the shock wave depends on the dimensions of the shock tube, the location in the tube at which the pressure is being monitored, the smoothness of the inner walls of the tube, the type and design of the diaphragm, and the temperature, pressure, and species of gas in each tube compartment. It may be in the order of milliseconds. The low frequency cutoff inherent in the shock wave is the reciprocal of the time the pressure is constant.

The rise time of the pressure step due to the shock wave is in the nanosecond range [3, 7, 10] and is therefore considered to be an idealized pressure step containing all frequencies above the low-frequency limit.

All the transducer calibration parameters listed above can be obtained by calibrating the transducer with a shock tube having a known pressure amplitude. The amplitude and phase, both as functions of frequency, are obtained from the transducer output as a function of time through Fourier transforms.

Some consider the shock tube to be a primary standard in that the pressure amplitude can be calculated, using shock tube theory, from the properties of the gases in the two compartments, the initial pressures and temperatures, and the measured shock speed [7, 11]. Others prefer to think of the shock tube as a reference standard calibrated using the fundamental molecular properties of a diatomic gas, measured via laser spectroscopy, and thereby avoiding the assumptions of shock tube theory [12].

Quick-opening valve devices. Quick-opening valve devices have been designed to generate both negative and positive pressure steps. For a negative step, a volume at high pressure that contains the transducer is quickly vented to a lower pressure such as the atmosphere. For a positive step, a large volume at high pressure is quickly vented into a small volume at low pressure containing the transducer. A device for generating positive steps up to 1,0 GPa with a rise time of "...well under one millisecond..." using a hydraulic fluid has been applied to ballistic studies [13]. Another device for generating positive pressure steps operates with gas at pressures up to 7 MPa and has a 35 μs rise time when helium is used [14].

An advantage of the quick-opening valve is that the amplitude of the pressure can be maintained for as long a time as the operator wishes after the valve has been opened, limited only by the length of the data recording time, which provides low-frequency data and allows time for accurate static measurements of the pressure amplitude. A gas-operated quick-opening valve device is considered to be an extension of the shock tube to low frequencies [15]. Due to the length of the rise time in a quick-opening valve device, some authors prefer not to assume it generates an idealized pressure step, but use a reference transducer calibrated by other means, such as a shock tube, to determine the shape and rise time of the pressure step [3, 11, 15].

Explosive devices. Explosive-driven pressure generators have been reviewed by Damion [11] and by Schweppe et al. [16]. It is more likely that such devices would be used in a military laboratory than in a national metrology laboratory. Variations in the pressures generated by explosives make it necessary to always use a reference transducer, calibrated by some other means, to measure the pressure.

Drop hammer. The transducer to be calibrated in a drop-hammer device is mounted in the side of a cylinder which is filled with an incompressible fluid (glycerine) and closed with a piston. A guided weight is then dropped on the piston and captured on the rebound. The resulting pressure pulse resembles a half-sine wave with a rise time on the order of milliseconds and mimics that observed in gun barrels. Such devices have been used at pressures up to 800 MPa. The metrological properties of the drop hammer have been thoroughly studied by Riegebauer [17].

3.2 Periodic pressure generators

As a class of instruments, periodic pressure generators suffer decreased pressure amplitude as the frequency increases and require a reference pressure transducer to measure the pressure amplitude [3, 11, 15, 18]. As such, they are more useful as comparators than as primary standards. A number of periodic generators are described in the literature, often designed to meet special measurement needs. The following examples serve to illustrate the techniques used:

Vibrating column of liquid. The test transducer and the reference transducer are mounted in mirror-image locations in the side wall of a vertical cylinder filled with fluid. The top of the cylinder is closed with a carefully fitted piston which is free to move vertically and serves as a seismic mass. The bottom of the cylinder is sealed and mounted on a shaker table. The device generates a peak pressure of 7 MPa and has a maximum frequency of 1 kHz [14].

Variable-volume generators. The transducer is mounted in the wall defining a small volume. One end of the volume is closed by a diaphragm or a piston which is motor-driven to vary the volume repetitively [3, 14, 18]. The volume is minimized to maximize the resonant frequency of the cavity. Schweppe et al. [18] describe a generator that is capable of generating a 1 MPa peak-to-peak ripple over a 3,5 MPa static pressure at frequencies up to 1 kHz.

Rotating valves. The design of the rotating valve device is suggestive of a plug valve. The transducer is mounted in a small cavity in the valve body. Two parallel holes serve to pressurize and exhaust the cavity. These parallel holes are interrupted by a larger hole drilled at 90° to them into which is fitted the valve plug. The plug has two holes drilled at 90° to each other such that one communicates with the pressurizing hole, and then upon rotation of 90°, the other communicates with the exhaust hole. The plug is rotated by a motor. The device is limited to a frequency of a few hundred hertz by distortion of the pressure pulses due to the inertia of the gas column in the valve system [18].

Sirens. In a siren the transducer is mounted on axis in one end of a cylindrical cavity whose length is tuned to act as a half-wave resonator. High-pressure gas is admitted through a side-wall port. The gas is vented on axis through the other end of the cavity. The siren wheel, a thin disk with a ring of evenly spaced, exhaust-port-sized holes near the periphery, is mounted such that its holes line up with the exhaust port. When the wheel is rotated, its holes repeatedly interrupt the gas flow from the exhaust port producing periodic pressures. Operating frequencies up to 1 kHz at pressures of 200 kPa have been reported [3, 18].

4. Dynamic Pressure Calibration Services at National Metrology Laboratories

Currently, France is the only nation whose national metrology system provides dynamic pressure calibration services traceable to national standards. This laboratory is under the direction of Professor J. P. Damion at the École Nationale Supérieure d'Arts et Métiers in Paris. Their primary standards are a series of shock tubes and quick-opening valve devices of overlapping range in frequency and pressure which have been cross-compared. They span the pressure range up to 20 MPa [15].

In the United States, the National Institute of Standards and Technology is developing a primary standard for dynamic pressure measurement. The pressure generators are a shock tube and a quick-opening valve device, both capable of 20 MPa. The shock tube has optical access for laser spectroscopy. The primary standard is to be based on the fundamental properties of diatomic gas molecules measured by means of laser spectroscopy [12].

References

1. Bean V. E., Rosasco G. J., Executive Summary, In *Proc. Workshop on the Measurement of Transient Pressure and Temperature* (Edited by V. E. Bean and G. J. Rosasco), NISTIR 4828, Gaithersburg, MD, National Institute of Standards and Technology, 1992, 1-6.
2. Lally R. W., Transduction, *Quartz Sensors,* Depew, New York, PCB Piezotronics, 1984, 135.
3. *A Guide for the Dynamic Calibration of Pressure Transducers,* ANSI MC88.1-1972, New York, American Society of Mechanical Engineers, 1972, 28 p.
4. Jones Jr. H. B., Knauer R. C., Layton J. P., Thomas J. P., *ISA Trans.,* 1965, **4,** 116-132.
5. Wylie Jr. C. R., *Advanced Engineering Mathematics,* 2nd ed., New York, McGraw-Hill Book Co. Inc., 1960, Chap. 6.
6. Schweppe J. L., Eichberger L. C., Muster D. F., Michaels E. L., Paskusz G. F., *Methods for the Dynamic Calibration of Pressure Transducers,* National Bureau of Standards Monograph 67, December 1963, 4-5.
7. Schweppe J. L., Eichberger L. C., Muster D. F., Michaels E. L., Paskusz G. F., *Methods for the Dynamic Calibration of Pressure Transducers,* National Bureau of Standards Monograph 67, December 1963, 77-86.
8. Glass I. I., Martin W., Patterson G. N., *A Theoretical and Experimental Study of the Shock Tube,* UTIA Report No. 2, Institute of Aerophysics, University of Toronto, November 1953, 281 p.
9. Glass I. I., Hall J. Gordon, *Handbook of Supersonic Aerodynamica,* Section 18, Shock Tubes, Navord Report 1488, Vol. 6, December 1959, 604 p.
10. Smith R. O., Lederer P. S., *A Shock Tube Facility for Dynamic Calibration of Pressure Transducers,* NBS Report 5941, July 1958, 16 p.
11. Damion J. P., *Bulletin BNM,* October 1977, 7-22.
12. Rosasco G. J., Bean V. E., Hurst W. S., *J. Res. Natl. Inst. Stand. Technol.,* 1990, **95,** 33-47.
13. Juhaz A. A., Bullock C. D., Newhall D. H., *Measurements and Control,* 1991, **146,** 123-127.

14. Lally J. F., In *Proc. Workshop on the Measurement of Transient Pressure and Temperature* (Edited by V. E. Bean and G. J. Rosasco), NISTIR 4828, Gaithersburg, MD, National Institute of Standards and Technology, 1992, 104-119.

15. Damion J. P., In *Proc. Workshop on the Measurement of Transient Pressure and Temperature* (Edited by V. E. Bean and G. J. Rosasco), NISTIR 4828, Gaithersburg, MD, National Institute of Standards and Technology, 1992, 182-194.

16. Schweppe J. L., Eichberger L. C., Muster D. F., Michaels E. L., Paskusz G. F., *Methods for the Dynamic Calibration of Pressure Transducers*, National Bureau of Standards Monograph 67, December, 1963, 69-75.

17. Riegebauer J., In *Proc. Workshop on the Measurement of Transient Pressure and Temperature* (Edited by V. E. Bean and G. J. Rosasco), NISTIR 4828, Gaithersburg, MD, National Institute of Standards and Technology, 1992, 151-181.

18. Schweppe J. L., Eichberger L. C., Muster D. F., Michaels E. L., Paskusz G. F., *Methods for the Dynamic Calibration of Pressure Transducers*, National Bureau of Standards Monograph 67, December, 1963, 87-95.